A MULTILEVEL DECOMPOSITION PROCEDURE FOR THE PRELIMINARY WING DESIGN OF A HIGH-SPEED CIVIL TRANSPORT AIRCRAFT

Peter J. Röhl
Graduate Research Assistant

Dimitri N. Mavris
Manager, Aerospace Systems Design Laboratory

Daniel P. Schrage
Director, Aerospace Systems Design Laboratory
School of Aerospace Engineering, Georgia Institute of Technology
Atlanta, GA 30332-0150

ABSTRACT

A multilevel decomposition approach for the preliminary design of a High Speed Civil Transport Aircraft wing structure is described. The wing design is decomposed into three levels. The top level uses the FLOPS aircraft synthesis program to generate preliminary weights, mission, and performance information. The optimization criterion is productivity expressed by a productivity index for the specified mission. The second level of the system performs a finite-element based structural optimization of the wing box with the help of the ASTROS structural optimization tool. The wing structure is sized subject to strength, buckling, and aeroelastic constraints. The buckling constraint information is supplied by the third level where a detailed buckling optimization of individual skin cover panels is performed.

KEYWORDS: Multidisciplinary Optimization, Multilevel Decomposition, High-Speed Civil Transport, Wing Structural Design

INTRODUCTION

As modern aircraft designs tend to become more and more complex in order to outperform previous models, new techniques in system design synthesis and optimization become increasingly important. This is especially true for the design of a second - generation supersonic transport aircraft as an example of a highly coupled system. At the same time, the methodology of multidisciplinary design and optimization is evolving into a new engineering discipline that seems most suitable to address this type of design problem where the traditional sequential approach will most likely lead to suboptimal results [1].

One obstacle for the fast evaluation of a relatively large number of candidate configurations in the development of a High-Speed Civil Transport Aircraft (HSCT) has been the long time, up to 24 months, for the completion of one full design cycle [2]. At the same time, studies performed in the 70s indicate that a sequential addressing of the strength and flutter problem in the structural design of a supersonic transport wing leads to severe mass penalties [3].

Paper Presented at the 1st Industry/University Symposium on High Speed Civil Transport Vehicles, Greensboro, NC, December 1994

All these factors combined clearly show the need for an integrated wing design procedure that is able to address structural design, aerodynamic, and aeroelastic questions early in the design process. The three-level wing design procedure presented in this paper can be regarded as a framework where additional modules, for example controls, more accurate aerodynamics, propulsion, etc. can be integrated at a later stage. The material presented here is based on ongoing efforts at Georgia Tech to develop, enhance, and implement the technologies of Concurrent Engineering (CE) and Integrated Product and Process Development (IPPD)[4], [5]. The focus of this paper is the implementation and further development of the multilevel decomposition scheme for HSCT wing design previously proposed [6], and the integration of a panel buckling optimization procedure into the ASTROS [7] (Automated Structural Optimization System) code within the three-level wing design procedure.

MULTILEVEL DECOMPOSITION APPROACH

General

As the resources necessary to solve an optimization problem typically increase at a much faster rate than the number of design variables, large optimization problems usually require some type of decomposition into smaller sub-problems [8]. According to the data transfer links between the sub-problems, different types of decomposition can be identified (Fig. 1). In a non-hierarchical decomposition data can be transferred between any two analysis blocks, whereas in a hierarchical type of decomposition each block only communicates with its direct parent or daughter problem - one parent problem can have several daughter problems, but each daughter problem can only have one parent problem associated with it. Hybrid types of decomposition contain both hierarchical and non-hierarchical elements.

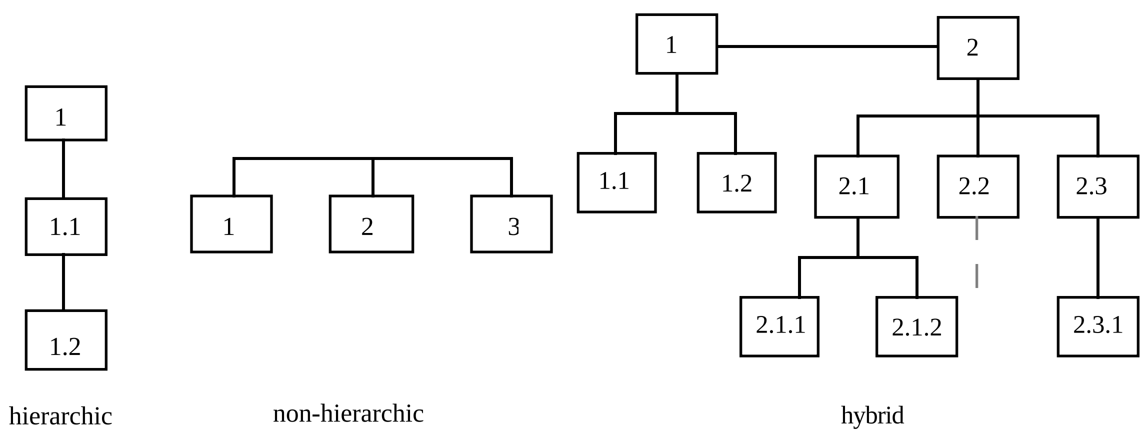

Figure 1: Types of Decomposition

Decomposition of the Design Task

The wing design procedure described in this paper lends itself very well to a hierarchical type of decomposition due to the data flow between the different levels (Fig. 2). The wing structural design problem is decomposed into three levels. At the top level, a general aircraft sizing and performance code sizes the aircraft for the specified mission based on statistical, empirical, and analytical methods. At the middle level the actual structural layout of the wing takes place based on a relatively crude finite element analysis. On the third level individual skin cover panels which are modeled as membrane elements with a smeared thickness at the second level are sized for buckling as stiffened panels.

One general problem with multilevel decomposition procedures has to be addressed at this point: The execution starts at the top level with an educated guess of the 2nd level results. Therefore, it is in general not guaranteed that there is a feasible lower level solution for that specific point in the upper level design space. In this specific case, though, this general problem is overcome in two different ways: As long as reasonable wing planform shapes and thicknesses are used in the top level, there will always be a feasible structural design able to carry the loads, at most at the penalty of a very high wing weight. Between the 2nd and 3rd level, the feasibility problem does not exist at all because the third level objective (buckling load) is handled as a constraint on the second level, therefore it is automatically striving to be fulfilled during the 2nd level redesign.

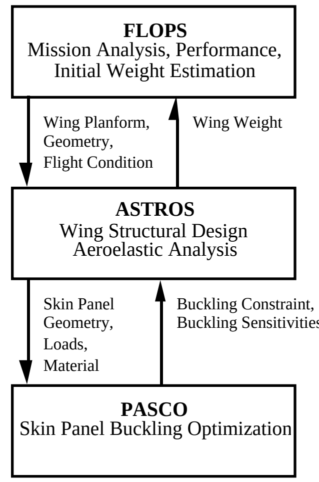

Figure 2: Multilevel Decomposition of the Wing Design Problem

Analysis and Design Modules

The top level uses the code FLOPS (Flight Optimization System) [9] developed by NASA Langley which has been modified for this application and for its integration into the multilevel scheme. FLOPS is a multidisciplinary system of computer programs for conceptual and preliminary design and evaluation of advanced aircraft concepts. It consists of nine primary modules for weights, aerodynamics, engine cycle analysis, propulsion data scaling and interpolation, mission performance, takeoff and landing, noise footprint calculation, cost analysis, and program control. Through the program control module, FLOPS may be used to analyze a point design, parametrically vary certain design variables, or optimize a configuration with respect to these design variables (such as minimum gross weight, maximum range, minimum cost, etc.). The configuration design variables include wing area, wing sweep, wing aspect ratio, wing taper ratio, wing thickness to chord ratio, gross weight, and thrust. The performance design variables are cruise Mach number and maximum cruise altitude. The engine cycle design variables are the design point turbine entry temperature, the maximum turbine entry temperature, the fan pressure ratio, the overall pressure ratio, and the bypass ratio for turbofan and turbine bypass engines.

The Productivity Index PI, defined as the ratio of aircraft productivity to the sum of fuel and empty weight,

$$PI = \frac{PL \cdot V_B}{W_e + W_f} \ , \tag{1}$$

has been selected as a measure of aircraft performance and has been programmed as a possible objective function. At a time when economic data for a supersonic transport aircraft are sketchy at best, the productivity index offers a measure of comparing different configurations by normalizing aircraft productivity (block speed times payload) with respect to an indicator of the cost involved in achieving this productivity. The denominator captures a part of both the operating costs (through the fuel weight which directly translates into fuel cost) and the acquisition cost which is usually calculated as a function of aircraft empty weight.

The structural optimization level uses the ASTROS code to design a minimum weight wing subject to a large number of stress, strain, displacement, and flutter constraints. ASTROS is a multidisciplinary analysis and design tool most suitable for the design of aerospace structures. It was developed for and by the Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, and has been continuously upgraded. The latest version being used now is Version 10. It combines finite-element-based structural analysis, aerodynamic and aeroelastic analysis with mathematical optimization algorithms in order to design a minimum weight structure meeting a variety of different types of constraints. The engineering analysis capabilities include both static and dynamic structural analyses (transient and steady-state) and static and dynamic aeroelastic capabilities. Design constraints include stress, strain, displacement, frequency, flutter, and aerodynamic constraints. Data storage and manipulation is performed by ASTROS' own database system (CADDB). Steady aerodynamic analyses in ASTROS are performed by the USSAERO code, while the Doublet-Lattice and constant pressure methods are used for unsteady analyses in the subsonic and the supersonic regime, respectively.

The standard ASTROS solution sequence has been modified to allow a stop and restart of the optimization procedure after a certain number of iterations in order to allow the designer to review the design progress and to facilitate the call to the panel buckling analysis on the third level of the multilevel decomposition scheme (Fig. 2).

The wing structure is modeled consisting of spars, ribs, and skin panels. The skin panels are modeled as membrane elements, the spar webs and the ribs as shear panels, and the spar caps as rod elements (Fig. 3). All these elements can be designed, whereas posts that connect the upper and lower wing surface are modeled as rod elements that are not designed and mainly serve the purpose of preventing the global stiffness matrix from becoming ill-conditioned.

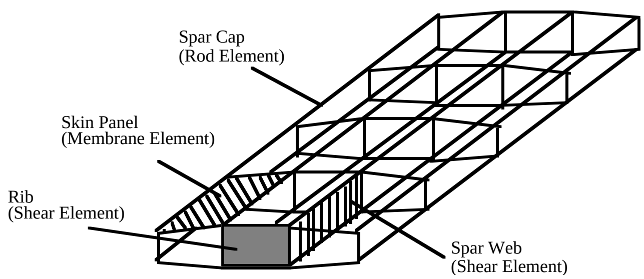

Figure 3: Wing Box Finite Element Model

The component level of the three-level procedure optimizes selected wing skin panels for buckling. It uses the code PASCO (Panel Analysis and Sizing Code) [10], [11] developed by NASA Langley. PASCO was developed for the buckling and vibration analysis and sizing of prismatic structures having an arbitrary cross section. PASCO is primarily intended for analysis and sizing of stiffened panels made of laminated orthotropic materials. When used in the analysis mode, PASCO calculates laminate stiffnesses, laminate stresses and strains, buckling loads, vibration frequencies, and overall panel stiffness. When used in the sizing mode, PASCO adjusts sizing variables to provide a low-mass panel design that carries a set of specified loadings without exceeding buckling or material strength allowables. For its integration into the multilevel decomposition procedure, PASCO has been extensively modified and a new design objective function has been programmed. It is possible now to design a panel with a fixed mass for maximum buckling load by redistributing the material onto skin and stiffeners. Reference [12] describes the PASCO upgrade in detail.

HSCT BASELINE CONFIGURATION

In order to be able to analyze different HSCT wing configurations, a baseline High-Speed Civil Transport was defined. Due to the availability of information at the time the baseline aircraft was established, the NASA HiSAIR project was the main source of the Georgia Tech baseline HSCT. The configuration used here is closest to the NASA HiSAIR configuration of 1992 [13], [14] with a range of 6500 Nm, 250 passengers and a wing area of 9000 ft^2. A FLOPS input file was compiled for this configuration. With this input, a

FLOPS run was performed in order to produce a converged design capable of flying the prescribed mission. FLOPS produced a configuration with a TOGW of 662166 lb, a fuel weight of 381941 lb and a productivity index of 108.36 Kts.

The 9000 ft^2 wing thus obtained (Fig. 4) has an aspect ratio of 2.678 and a leading edge sweep of 73^o inboard and 43^o outboard. The resulting wing span is 155.25 ft. Information about the wing thickness and airfoil was not available, so a 3% thick airfoil was assumed, and for all the latest configurations analyzed an actual NACA 62003 airfoil was used as an envelope for the wing box.

The baseline mission specified for the calculations consists of 10 min. taxi and warm-up, take-off at sea level, standard day, climbout at 250 Kts TAS, accelerating climb to the initial cruise altitude of 56000 ft, then a supersonic cruise at Mach 2.4 and optimum altitude for maximum specific range to the destination. After descent, landing and taxi for 5 min., standard reserves for a flight for 250 Nm to an alternate airport at 10000 ft and a holding time of 30 min. are taken into account (see Fig. 5). This is a simplified mission that is just being used to establish the methodology. There is no doubt that a real HSCT mission will have to include a subsonic cruise part since supersonic cruise over populated areas will most likely not be possible due to sonic boom constraints.

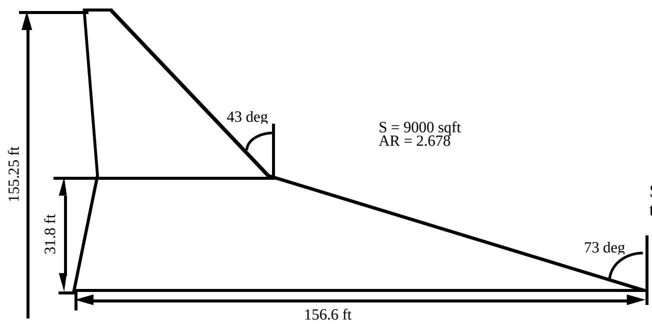

Figure 4: HSCT Baseline Wing

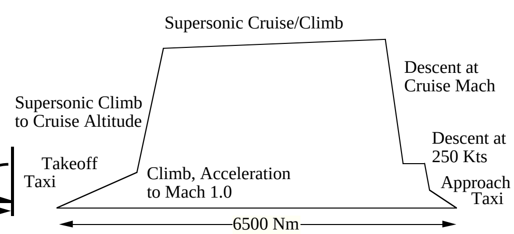

Figure 5: Mission Profile

Wing Finite Element and Aerodynamic Models

The ASTROS finite element model of the HSCT baseline wing consists of four main spars and five ribs in the inboard and seven in the outboard section. Skins are modeled as membrane elements, spar webs and ribs as shear panels, and spar caps and posts as rod elements, see Fig. 6. The fuselage is represented by a stick model of beam elements containing non-structural mass to account for payload and systems. The engines are modeled as mass-containing rod elements that are attached to the wing box via connecting rods. Both a free-free boundary condition and a clamped boundary condition have been defined, where the first is used for the aeroelastic and steady aerodynamic analyses, the latter for static analyses.

The four-spar-model consists of 569 elements, out of which 421 are designed, linked to 51 to 62 design variables. 62 design variables are used for the buckling optimizations, where only the top skin panels are buckling critical. In the other cases top and bottom skin panels are linked to the same design variables.

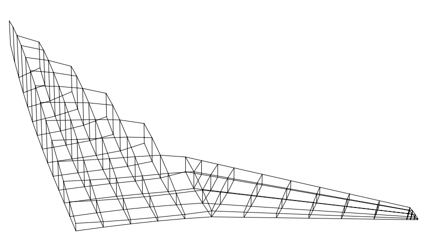

Figure 6: 4-Spar Finite Element Model

CONCLUDING REMARKS AND OUTLOOK

Due to severe space limitations, the authors chose to present the design methodology only as it is being implemented for the HSCT wing design. The integration of the structural optimization with the skin panel buckling procedure is complete and initial results have been obtained [15]. The addition of the design synthesis program to the three-level structure is currently on progress and results are expected soon. The results obtained so far show roughly a 10% mass penalty for the inclusion of a low-altitude subsonic flutter constraint above the static only design and a drive towards increasing the torsional stiffness of the wing through increased skin panel thicknesses. The critical flutter mode is a combination of the first wing bending and the first torsional modes. Inclusion of top skin panel buckling constraints adds roughly another 20% to the designed wing weight. As it was mentioned before, detailed results can be obtained from reference [15].

Overall the results obtained so far are very promising and seem to indicate the validity of the methodology developed. Complete verifications of the procedure will be presented in the future with the help of results for supersonic configurations obtained in [3] and more recent HSCT results from various sources once the implementation is complete.

REFERENCES

[1] Sobieszczanski-Sobieski, J.: Sensitivity Analysis and Multidisciplinary Optimization for Aircraft Design: Recent Advances and Results, Journal of Aircraft Vol.27, No. 12, December 1990

[2] Bhatia, K.G.; Wertheimer, J.: Aeroelastic Challenges for a High Speed Civil Transport, AIAA 93-1478, 34th Structures, Dynamics and Materials Conference, La Jolla, CA, April, 1993

[3] Sakata, I.F.; Davis, G.W.: Substantiating Data for Arrow-Wing Supersonic Cruise Aircraft Structural Design Concepts Evaluation, Vol. 1-4, NASA CR-132575, Lockheed California, 1976

[4] Schrage, D.P.; Rogan, J.E.: The Impact of Concurrent Engineering on Aerospace Systems Design, 1991

[5] Schrage, D.P.: Introduction to Concurrent Engineering, Class Notes, Fall 1992

[6] Röhl, P.J.; Schrage, D.P.: Multidisciplinary Wing Design of a High Speed Civil Transport Aircraft by Multilevel Decomposition Techniques, AIAA 92-4721, 4th AIAA/Air Force/NASA Symposium on Multidisciplinary Analysis and Optimization, Cleveland, OH, September 1992

[7] ASTROS Version 10 User Manuals, Universal Analytics, Inc., Torrance, CA, March 1993

[8] Haftka, R.T.; Gürdal, Z.; Kamat, M.P.: Elements of Structural Optimization, Kluwer Academic Publishers, Dordrecht 1990

[9] FLOPS User's Guide, Release 5.0, NASA Langley Research Center, November, 1992

[10] Anderson, M.S.; Stroud: PASCO Structural Panel Analysis and Sizing Code, Capability and Analytical Foundations, NASA Langley Research Center, NASA-TM 80181, November 1981

[11] Anderson, M.S.; Stroud, W.J. et al.: PASCO Structural Panel Analysis and Sizing Code, User's Manual, NASA Langley Research Center, NASA-TM 80182, November 1981

[12] Röhl, P.J.: Implementation of Minimum Buckling Load as a New Optimization Objective in the Buckling Code PASCO, Progress Report, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, Winter 1994

[13] Coen, P.G.; Sobieszczanski-Sobieski, J.; Dollyhigh, S.M.: Preliminary Results from the High Speed Airframe Integration Research, AIAA Paper 92-1004, 1992

[14] Barthelemy, J.-F. M.; Wrenn, G.A, et al.: Integrating Aerodynamics and Structures in the Minimum Weight Design of a Supersonic Transport Wing, AIAA Paper 92-2372, April 1992

[15] Röhl, P.J.; Mavris, D.N.; Schrage, D.P.: A Multilevel Optimization Procedure Centered on the ASTROS structural Optimization System, 5th AIAA/Air Force/NASA Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September 1994